LA-11781-MS

Requirements for Progressive Strategic Defenses

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Prepared by Bo West, P Division

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Accession Number: 3026

Publication Date: Mar 01, 1991

Title: Requirements for Progressive Strategic Defenses

Personal Author: Canavan, G.H.

Corporate Author Or Publisher: Los Alamos National Laboratory, Los Alamos, NM 87545 Report Number: LA-11781-MS

Report Prepared for: U.S. Dept. of Energy

Descriptors, Keywords: SDS SDI Requirement Progress Strategy Defense Concept Analysis ALPS GPALS Space Base Countermeasue Cost Survivability Decoy Discrimination Deployment Development

Pages: 00039

Cataloged Date: Jul 18, 1991

Contract Number: W-7405-ENG-36

Document Type: HC

Number of Copies In Library: 000001

Record ID: 22271

Source of Document: DoE

LA-11781-MS

UC-700
Issued: March 1991

Requirements for Progressive Strategic Defenses

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REQUIREMENTS FOR PROGRESSIVE STRATEGIC DEFENSES

by

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ABSTRACT

Space-based layers face countermeasures, cost, and survivability concerns. Midcourse defenses face decoys, which they must discriminate. Simple models indicate that their initial deployment should be effective and that development could improve their effectiveness. That would provide a hedge against uncertainty and an incentive to the reduction of offensive forces.

I. INTRODUCTION

The diffusion of missile and weapon technology has produced threats that range from accidental launches to large-scale exchanges.[1] The goals, concepts, and prospects for defenses against these threats are discussed elsewhere.[2] This report discusses the technical performance of current defensive concepts relative to those requirements.

Section II, which reviews current concepts and performance, is not essential for the understanding of subsequent sections. Section III reviews the threats from and requirements for defense against accidental, unauthorized, third country, or subnational attacks. Section IV reviews the requirements for defense against large-scale attacks on missile silos, mobile missiles, bombers,

command, control, communication, and other targets, concluding that useful levels of defense against each could be possible given expected performance and costs.

II. CONCEPTS AND ANALYSIS

The main defensive layers are boost, midcourse, and terminal. The first is the region over the launch area where missiles accelerate and deploy their weapons and decoys; the second is the long ballistic portion of the objects' trajectories; and the third is the region where they reenter over their targets. The physical basis for the defensive concepts have been discussed extensively.[3] This section reviews the factors that determine their performance or limit their scaling.

A. Boost Layer

The boost phase is preferred because missiles can be destroyed before their weapons and decoys are deployed, but it lasts only a few hundred seconds and can be compressed further geographically.[4] The two main classes of defenses in the boost phase are kinetic- and directed-energy defenders.

1. Kinetic-Energy Defenders

Kinetic-energy defenders home on and run into missiles at high velocity. Their probability of kill is high, and their cost is much less than that of the missiles, so their cost effectiveness should be high.[5] However, only a fraction of the defenders would be over the launch area at any given time; most would be elsewhere in their orbits. In extended engagements, all defenders would rotate over the launch area in a few hours, so all could participate in the defense.

For simultaneous launches in the near term, however, only about 20% of the defenders would be within range. If the missile launch area has effective radius W, the missiles' acceleration and deployment time is T, and the defender's velocity is V, defenders within a range

$$R = W + V \cdot T \tag{1}$$

of the center of the launch area could reach the missiles during boost. A geometric estimate of the fraction of the defenders available is

$$f \approx z\pi R^2/4\pi R_e{}^2 = z[(W+VT)/2R_e]^2, \qquad (2)$$

where R_e = 6,400 km is the Earth's radius. The inverse of f is referred to as the "absentee ratio," to which the size and cost of defensive constellations are proportional. Current values, W $\approx$ 1,800 km, T $\approx$ 600 s, and V $\approx$ 6 km/s, give R $\approx$ 5,400 km, which would allow $\approx$ 18% of the constellation to engage missiles during boost. Inclining orbits over the launch area increases the fraction of defenders in range by a factor of[6]

$$z \approx 2.5/(W+VT)^{1/2}, \qquad (3)$$

where W and VT are in Mm. For the parameters above, z $\approx$ 1.1, which would increase near-term defender availability to f $\approx$ 20%. A launch of M missiles would require M/f defenders, which in the near term would be about 1,000/0.2 $\approx$ 5,000.

A partial deployment of K defenders could kill at most fK missiles. The number would actually be about pfK because the defenders' kill probability of p $\approx$ 0.9 would let $\approx$ 10% of the missiles survive the first volley, and a second volley could be expensive. It could reduce the 10% leakage to $\approx$ 1%, but would require another $\approx$ 1,000 interceptors to do so. Thus, its cost per kill would be about 10 times that of the first volley. Directed-energy concepts have long ranges, so they could provide a second volley cheaply with a minimum of additional platforms.

Currently, W $\approx$ VT, so decreasing W or T alone would at most decrease f by a factor of $\approx$ 4. Both must be decreased for full effect. In the midterm the Soviets decreased W and T by a factor of 2 each as part of their ongoing force modernization program.[7] If so, geometric availability would drop by a factor of 4, z would increase to $\approx$ 1.5, f would fall to $\approx$ 7%, and the absentee ratio would increase to 1/f $\approx$ 15.

An additional factor of 2 decrease in W and T in the long term would reduce T to the minimum time required for a missile to clear the atmosphere and deploy its weapons and decoys and decrease the launch area to essentially a point. That would

decrease the defenders' geometric availability by another factor of 4, increase z to ≈ 2.2, decrease f to ≈ 2.4%, increase absenteeism to 1/f ≈ 40, and the number of missiles to ≈ 1,000/f ≈ 40,000. These geometric estimates agree to within 10-20% with more exact solutions.[8] The defenders could increase V to improve their availability, but the improvement is only logarithmic; the value of 6 km/s used above is appropriate through the mid term.[9] Very small, ultra high velocities would be useful, but have received less development.[10]

Current heavy missiles have life-cycle costs of ≈ $ 200 M;[11] current space-based interceptors ≈ $ 20 M,[12] for which the defense would have a cost-effectiveness ratio of ≈ $ 200 M/($ 20 M·5) ≈ 2:1. That would be adequate initially, but if midterm deployment of fast missiles and compact launch areas reduced the fraction of defenders available to ≈ 7%, the cost effectiveness of initial interceptors would fall to ≈ 1:1. In the long term, the fraction might fall to 2-3%, for which the ratio would be ≈ 5:1 in favor of the offense.

If defender's cost and availability fell proportionally, their cost-effectiveness ratio should stay about constant through the transition. Thus, reducing the cost of defenders by an order of magnitude is properly the thrust of current research on "brilliant pebbles."[13] For $ 2 M defenders, even for an absentee ratio of 40, the defenders would have a cost-effectiveness ratio of ≈ $ 200 M/($ 2 M·40) ≈ 2.5:1, which is not commanding, but could be adequate. Countermeasures and mobile missiles should not degrade defender economics significantly. Thus, if attempts to reduce costs are successful, kinetic energy could remain a viable defense concept into the long term.[14]

2. Directed Energy

In the boost layer the various laser and particle beam directed-energy concepts scale similarly. Their growth and cost were initially confusing,[15] but it is now understood that each concept should have favorable economics for projected costs and less sensitivity to launch time and area than kinetic energy.[16]

Each has problems. Space-based lasers are large, limited, and sensitive to missile hardening.[17] Ground-based lasers are cheaper[18] but have lossy, unprotected uplinks.[19] Particle beams can penetrate shielded targets, but have propagation constraints.[20] No concept is dominant, but none is excluded. All could continue to compete, although if time was of the essence, in a few years one could be picked for faster development on the basis of current programs.

The number of laser satellites, N_L, of brightness B required to negate M missiles of hardness J that are launched from an area A and are vulnerable for time T is

$$N_L = C(JM/BA_ET)^{\Gamma}, \tag{4}$$

where C is a constant determined by the solution, $A_E \approx (A_oA)^{1/2}$ is an effective launch area, $A_o \approx 10\ \mathrm{Mm}^2$ is the current launch area, and $\Gamma \approx 0.7$-0.8 for medium- to high-brightness lasers. Other directed-energy concepts scale similarly.[21] If B remained fixed and A and T decreased proportionally,

$$N_L \propto (A_ET)^{-\Gamma} \propto (WT)^{-\Gamma} \propto T^{-2\Gamma} \approx T^{-3/2}, \tag{5}$$

which is somewhat weaker than kinetic energy's T^{-2}, although over two decades, i.e. about a fourfold reduction in W and T, the difference would only be a factor of $\sqrt{T} \propto \sqrt{4} = 2$. If the lasers' brightness increased, however, the difference would be larger by a factor of B^{Γ}, which could be large due to their potential growth rates.

About 50 lasers of 20-MW power with 10-m-diameter mirrors could negate the simultaneous launch of 1,400 fast missiles and buses that were vulnerable for 100 s.[22] For these long-term conditions, kinetic energy would need about $40 \cdot 1{,}400 \approx 60{,}000$ defenders. For \$ 2 M defenders and \$ 500 M lasers, the ratio of costs would be $\approx \$\,2\,\mathrm{M} \cdot 60{,}000 \div \$\,500\,\mathrm{M} \cdot 50 \approx 5$. Thus, directed-energy concepts could significantly reduce the cost per intercept when they become available. Their constellation size and cost should remain about constant, independent of threat modernization rates. Their cost effectiveness relative to modernized threats is about 2-3 times greater than that of space-based interceptors,

which gives directed energy considerable margin against cost growth.

Directed energy's main drawback is its perceived immaturity relative to kinetic energy. Discussion has centered on the time needed to develop large, bright platforms.[23] If, however, it was used as a supplement to or phased replacement for kinetic energy rather than as an alternative to it, modest directed-energy platforms should suffice[24] and could be available when needed.[25] Because of the long ranges of even modest platforms, they could provide a second volley cheaply with a minimum of additional platforms, which could reduce overall leakage to low levels. The main issues for directed energy appear to be reducing mass and cost, maintaining survivability, and expediting availability. They are not discussed explicitly here; the arguments below are for largely kinetic-energy defenses. The differences in constellation size and cost are discussed in a companion note.[26]

3. Sensors

Booster signatures are complex but bright and hard to mask or simulate. Post-boost vehicles are dimmer and hence harder to intercept, although that is possible, particularly with active measures. Battle management is a concern for kinetic-energy concepts. Autonomous operation would, in the near term, degrade the performance only a few percent, but in the midterm the degradation could be 30%. Efficient allocation is required. The issue is whether it should be synthesized by the defenders themselves or provided by external platforms. The cost of external sensors is an issue, but because of their size, survivability is a greater concern.[27]

Boost-phase early warning and track satellites watch the boost phase from geosynchronous orbits; from there sensors with current sensitivity and resolution can only track boosters, not buses or reentry vehicles (RVs). For the defenses considered here, it wouldn't be much of an improvement over current warning systems. Midcourse sensor satellites are closer, but they can only determine the tracks of buses, not RVs. Thus, it should be

about as effective, and much cheaper, to launch probe sensors on warning. None of the IR sensors can discriminate. IR signatures are barely big enough for them to track, let alone discriminate RVs and decoys.

No current sensor can determine a weapon's target before it is released from the bus, so boost-phase kills randomly reduce the total number of missiles headed at all targets. Statistical fluctuations lead to some targets being targeted by more penetrating weapons than others, but the identities of those targets cannot be chosen in advance.

B. Midcourse Layer

In midcourse the main concern is discrimination rather than lethality; using ground-based interceptors appears to be an efficient way to destroy the weapons found.

1. Defenders

Ground-based midcourse defenders' costs are modest because they are free of absenteeism. Space-based kinetic-energy defenders could in the near term maneuver to the threat from almost anywhere on the globe in the near term, but they would be at an economic disadvantage relative to ground-based defenders because of their launch costs, which would effectively be paid twice. Lasers are relatively ineffective in attacking reentry vehicles, which are intrinsically hard, but particle beams, whose energy is deposited in depth, could attack reentry vehicles effectively.[28]

2. Discrimination

The greatest concern in midcourse is the numerous decoys possible there. Heavy decoys could be addressed effectively by ground-based defenders even without discrimination, but light decoys are too numerous and cheap to shoot. They must be discriminated instead. There are three leading candidates: passive infrared sensors, active lasers and radars, and interactive directed energy.

Passive infrared sensors are developed and affordable. They are good bulk filters and capable of detecting small differences in emissions, areas, and motions. In recent years, however, it has proved possible to match all three quite accurately. At present there is a race between sensors and decoys, but by midterm it is unclear that any useful surface features will remain as passive sensor discriminants.

Lasers and radars examine objects actively with high resolution. They can detect even more subtle differences, but those differences can also be masked, so active sensors share with passive sensors the limitations that come from seeing only object's surfaces. It would be difficult to provide the power they require in space. Ground-based radars relax that constraint but share the vulnerabilities of earlier ground-based ABM sensors. Their doppler imaging could provide some discrimination, but it wouldn't survive long enough to contribute in large attacks. It would lose its doppler bandwidth after the first few exoatmospheric bursts and degenerate into a tracking radar.[29]

Directed energy can deliver enough energy to remote objects to perturb their motions or probe their interiors. Lasers create blowoff, which causes objects to recoil, although some materials absorbed without producing much recoil. Laser discrimination rates are modest. Particle beams can probe an object's interior, which determines its mass, the one weapon parameter a decoy cannot afford to duplicate. Modest particle beam constellations could discriminate heavily decoyed threats.[30] The principal concern with particle beams is their availability, which is delayed relative to other directed-energy concepts. That could be avoided by ground basing, which could reduce constellation sizes, beam energies, and currents.[31]

3. Defenses

Three types of defenses are possible in midcourse: random, preferential, and adaptive preferential. Random defenses would act in midcourse as in boost to reduce the total number of

objects in the threat. For simple threats, that could be adequate. Accidental, undecoyed threats might involve ≈ 10 weapons, which a similar number of defenders could negate. For $M \approx 400$ missiles with $m = 10$ weapons each against $I \approx 2{,}000$ ideal interceptors, the number of surviving weapons would be $\approx 2{,}000$. If they were targeted on $N \approx 1{,}000$ missile silos, for which their kill probability was $\approx 80\%$, the expected number of surviving retaliatory missiles would be $\approx (1-0.8)^2 \cdot 1{,}000 \approx 40$, or 4%. For limited but heavily decoyed threats, the number of objects could increase to 1,000-10,000, for which the number removed by 2,000 interceptors would only be a $\approx 20\%$ effect. A full, decoyed attack could involve 10^5-10^6 objects, for which random defenses would be prohibitive.

For limited defenses, effective discrimination and efficient allocation of defenders are needed. Passive discrimination could be adequate for modest, near-term threats, but interactive discriminants would be needed for mid- and long-term threats. Given discrimination, midcourse defenses can act preferentially. By protecting only a fraction of the targets, they could save more missiles than would survive with random defenses.

If there was an average of mM/N weapons targeted on each silo, by committing the same number of interceptors to it, the defense could assure the survival of any given silo. The number of missiles that could be protected with I interceptors is thus

$$S = I/(mM/N) = N \cdot (I/mM). \quad (6)$$

The fraction of surviving missiles is equal to the ratio of the number of interceptors to the number of attacking weapons. For the example above, that fraction is $I/mM = 50\%$, which is an order of magnitude greater than the 4% that would survive with random defenses. That should be adequate for military targets, though not for value. With further deployment, the fraction could grow.

Preferential defenses have been analyzed for several decades, but were less attractive with the short-range interceptors then available, which an attacker could degrade by varying the number of weapons allocated to various silos. If a silo with the average R/M defenders was attacked by $R/M + 1$

weapons, all of the defenders would have been negated by 1 additional weapon for no gain. The interim solution was to add more defenders to each defended silo, but the number needed could approach ≥ 2 for typical defender parameters.

Current long-range defenders are less susceptible to such countermeasures. Given sensors that can inspect the threat at range and determine any variations in the attack, long-range interceptors could defend lightly attacked targets, which would make variations in the threat beneficial to the defense. Adaptive defenses go further to exploit the variations produced by boost-phase defenses.[32] Their impact would be particularly large in the near term when few defenders were deployed. They do, however, have stringent requirements on information-gathering and transmission.[33]

Decoys degrade these results. For D undiscriminated decoys per weapon and simple preferential defenses, the number of defenders needed to protect a given target becomes $(D+1)mM/N$, and Eq. (1) is replaced by

$$S = I/[(D+1)mM/N] = N \cdot [I/(D+1)mM]. \qquad (7)$$

For the example above, the fraction surviving an attack with $D \approx 10$ decoys for $I = 2,000$ would be ≈ 5%. That could still be acceptable, but for $D = 100$ it would drop to ≈ 0.5%, which would not be. Degradations of adaptive preferential defenses are similar. For midcourse to be effective, good discrimination is essential.

C. Terminal Layer

Terminal, endoatmospheric intercepts are potentially the least expensive kind, but are subject to a number of atmospheric limitations that limit their effectiveness.[34] Nonnuclear counterparts to earlier ABM systems' interceptors have been developed. The analysis of terminal-phase defenses is essentially the compounding of probabilities to achieve a desired probability of survival. Nuclear-induced blackout and redout, however, limit the number of intercepts to about one, which in a multilayer defense would be useful but not pivotal.[35]

The principal interceptors are the HEDI and the short-range FLAGE. HEDI is a large, fast endoatmospheric interceptor with a delicate IR homing sensor. Even if its sensor could open in time to intercept, HEDI could probably only provide about one intercept over each site due to fratricide. FLAGE is a simpler interceptor that could probably do about as well.

Endoatmospheric interceptors tend to have small footprints, so they can only protect one or a few targets, which leads to redundancy. In principle, that could be altered by interceptors that could be launched on warning and loiter over the defended targets. In practice, such interceptors are avoided because of their sensitivity to false alarms and trajectories. Loitering systems could reduce cost, increase coverage, and increase the terminal phase's contribution significantly, but they have not been pursued.

D. Combined Defenses

Midcourse defenses can be combined favorably with those in the boost phase. From Eq. (2), the maximum number of boost-phase kills by kinetic defenders is $\approx fK$, but that is reduced to pfK by the interceptor kill probability p. With that reduction in the boost phase threat, Eq. (7) is replaced by

$$S = N \cdot [I/m(1+D)(M-pfK)]. \tag{8}$$

Figure 1 shows the result of combined boost and preferential defenses for an undecoyed near-term attack of 500 missiles with 10 RVs apiece. The bottom curve for $K = 0$ is straight, showing the $S \propto I$ scaling of Eq. (8). That also holds for $K = 500$, for which $S \approx 1{,}000$. For $K = 1{,}000$, the curve breaks at $I = 3{,}000$ where S reaches the total number of retaliatory missiles. For $K = 1{,}500$, the break is at about 2,000.

Figure 2 shows the number of survivors for midterm conditions. The curves are similar to those in phase one, but to achieve these levels of survivability it is necessary to use about twice as many interceptors. From Eq. (8), if K increases as $M/f \propto T^2$, the same level of performance should be maintained over time.

That performance is eroded for decoyed threats. Figure 3 shows the near-term performance for D = 10 decoys per RV. The curves are all linear, because none reaches saturation, i.e. high levels of survivability. For I = 3,000 and K = 1,500, the number of surviving missiles is ≈ 130; for the midterm, Fig. 4 shows that combination would only save ≈ 90.

Figure 5 shows midterm performance as a function of D for I = 1,000. The bottom curve is for K = 2,000; the top for 6,000. Both fall sharply with D. If some number of surviving missiles, say S = 200, is selected as an adequate deterrent, the 6,000 boost-interceptor curve could reach that number for D ≈ 16, but the 2,000 defender curve would fall below it for D ≥ 4. Unless very low levels of surviving forces are adequate, effective discrimination is needed. The analysis is similar but more cumbersome for adaptive preferential defenses.[36]

The selection of the combination of boost-phase and midcourse defenders that maximizes the survivors has been studied for cases of interest. The result, as expected from the discussion above, is that when discrimination is either very good or completely unnecessary the less expensive midcourse layer is favored, but if discrimination is poor or the threat is highly decoyed, the boost phase is preferred.[37]

A simple example is shown in Fig. 6, which gives S as a function of K. The bottom curve is for D = 10; the top is for 40. The bottom curve slopes upwards. Hence the least expensive combination would use only preferential interceptors, for which the cost would be ≈ $ 20B. The top curve for D = 40 slopes down; for it, boost-phase interceptors would be preferred. The cost would be about $ 50 B, roughly twice that for D = 10. The value for which the two slopes are equal gives the number of decoys for which the defense would be indifferent between boost and midcourse defenses, which is at D ≈ 30. Thus, for current cost and performance parameters there is a reasonable overlap between the overall effectiveness of boost and midcourse defenses and clear criteria for differentiating between them.[38]

E. Overall Effectiveness

The boost layer is attractive because of the leverage that results from killing many weapons and decoys per intercept. There are many defensive concepts, few decoys, and reasonable survivability. Kinetic- and directed-energy defenses could provide adequate lethality, and sensor requirements are not stressing. The main problem is the attacker's ability to compress the launch in space and time, which could severely limit the number of intercepts possible in boost in the mid and long terms. The defense can counter with cheaper defenders, which should be able to offset those offensive countermeasures. That competition could be a close race; its outcome is not known.

Midcourse has adequate lethality; the main concern is discrimination--particularly in the mid and long terms. There is arguably a progression from passive concepts in the near term, through active concepts in the midterm, to interactive concepts in the long term, but it is critically dependent on progress in advanced sensors and on unobservable developments in the threat. Survivability is also a concern; connectivity must be maintained if the information is to flow to later phases, as is needed for effective defenses.

In each layer, there are a number of new concepts, which appear to evolve at rates limited by resources rather than physics. Meanwhile, projects that were started before the SDI continue after their effectiveness is no longer clear at the expense of the cheaper defenders and the better discrimination that are essential. The boost and midcourse layers could each provide reasonably effective layers. Together they could approach the performance levels required to address long-term goals.

III. LIMITED PROTECTION

There are no formalized missions below Phase I's partial missile threat negation, but there are limited threats that are significant, tractable to limited defenses, and not susceptible to current deterrence through threat of retaliation.

A. Accidental Launch Protection

Despite the safety mechanisms built into missile launchers, an accidental launch could occur. While there has been no such incident, it cannot be excluded that, in the future, mechanical, electrical, or human failures could lead to the accidental launch of a strategic missile. There are other ways of attempting to prevent accidental launches, such as mechanisms for destroying them after launch, but they have not as yet been accepted by the military, in part due to concerns that the destruct code could be compromised.[39]

Presumably, such launches would consist of one or several missiles. If so, depending on whether it occurred in the near, mid, or long term, it could contain 0-100 decoys per weapon. The threat presented to the defenses would then consist of ≈ 10 weapons and up to ≈ 1,000 decoys. That is a factor of 10-1000 fewer than the number that near- or long-term defenses could face, but it could still be stressing if each missile had multiple weapons and penetration aids. The cost of a defense based on only a few tens of ground-based interceptors should be small compared to the damage expected without them, but it could still be significant for large, deployed launches.

Accidental launches from submarines in port or bastion would be similar to accidental land launches. Submarines close to the U.S. shore would stress defenses more. The accidental launch of a single missile could be addressed with current interceptor and radar technology; a full load would require performance approaching that for phase one. Destruct-after-launch mechanisms would be further complicated by an underwater submarine's physical isolation from the missile after launch and its intentional isolation from command and control to enhance its security.

1. Midcourse

Midcourse defenders, e.g., the exoatmospheric reentry vehicle intercept system (ERIS), could be effective against small

launches with few decoys. For the accidental launch of 10 weapons, 10-20 ERISs should provide a valuable level of protection. With warning from existing satellites and radars, the defenders could be based at a midcontinent location. It is possible that those sensors could also provide discrimination. For accidental launches, the sensors' lack of survivability should not be disqualifying; it would be improbable for accidental launches to first target vulnerable radars or synchronous satellites.[40]

Radars are currently the best-developed discrimination tools. If fully effective, they could reduce heavily decoyed attacks to the 10-20 interceptors per missile estimated in the previous paragraph. There is, however, a competition between decoys and sensors that could eliminate useful discriminants. If so, radars would only be partially effective. The deployment of penetration aids would reduce their effectiveness further. If they could only discriminate ≈ 50% of the decoys from a missile with 50 decoys per weapon, that would leave ≈ 250 objects, which would require 250-500 ERISs. For several missiles, the number would be even greater. The cost of the defenses, though great, would not be the issue. For limited defenses, feasibility, not cost effectiveness, is the issue. Command and control for such a large number of defenders could, however, approach that required for deliberate attacks.

For accidental submarine launches from port or bastion, the issues would be similar to those for land launches; those close to U.S. shores would be more stressing. Close-in deployments have been used by both sides, presumably for time-urgent missions like airbase attack, for which the shorter timelines of depressed trajectories would be useful. Missiles on depressed trajectories barely leave the atmosphere, however, so existing radars would be inadequate, and current midcourse defenders not necessarily adequate.[41] Radars could be fixed or replaced; modifying defenses to intercept depressed trajectories would be more difficult. The small footprints of current endoatmospheric

interceptors would require that they be deployed in large quantities throughout the U.S.

2. Boost Phase

The constellation sizing for intentional land launches discussed above is also appropriate for accidental launches, because the optimal coverage would be the same, although the number of defenders required could be reduced accordingly. In the near term, the fraction of defenders available would be $\approx$ 20%, which means that the constellation should contain about 5 times the number of missile launches expected. For a single missile, that would be 5-10 defenders; for a 10 missile complex that would be 50-100 defenders. If they operated with existing warning and command and control, they should cost $\approx$ 5-10·$ 1 M $\approx$ $ 5-10 M. In the midterm, those sizes and costs should increase by about a factor of 4.

A significant advantage of a boost-phase defense is that it is insensitive to the number or type of decoys or weapons carried. Such sensitivities could disqualify midcourse defenses in the long term.

Against accidental submarine launches from port or bastion, the number of defenders required would be similar to those for land launch. The main differences between a submarine launch from there and a land complex would be that submarines have longer burn plus deployment times. The impact can be estimated from Eq. (2) with $W = 0$. If submarine-launched missiles had twice the time of land missiles, the number of defenders required would be the same.

For accidental launches close to shore, the main issues are warning and apogee. On minimum-energy trajectories, the missile's bus would rise to 250 km for a 1,000-km range, although still taking $\approx$ 600 s to deploy. Defenders deployed to negate land launch accidents could also address close-in submarine launches. Constellations optimized for near-term land launches at 50-60° latitude have about a factor of 2 less concentration at the U.S.'s latitude of 30-45°. Thus, for the same size of

launch, perhaps twice as many boost-phase defenders should be deployed, or ≈ 10 per missile, expected in mid term.

For shorter ranges and depressed trajectories, intercepts are more difficult. They are of interest; presumably submarines would come in that close because they had time-urgent missions for which such trajectories would be appropriate. Current space-based interceptors would lose sensors and controllability below ≈ 100 km. Missiles lower than that would not be intercepted. Depression of their trajectories to 20-30° above the horizontal is comfortable; 10° is plausible. For 1,000-km range and 30°, the apogee is 150 km, which would just be attainable; for 20°, it is < 100 km, which is not. For boost-phase defenses, the main sensitivities are apogee and time line. Improving space-based defenders' performance in either parameter would become increasingly difficult for closer, lower trajectories.[42]

3. Terminal

As noted above terminal layers are only one more layer in terminal defenses. They play the same role in accidental land or bastion launches. For close-in, depressed submarine launches, however, their role is magnified because they could be the only layer. Current interceptors would have to be dispersed widely; loitering systems would not. That distinction is small here, however, compared to the observation that the depressed launches of concern remain in the atmosphere, and hence cannot use decoys effectively. Thus, at each site it would be necessary to deploy only enough of either type of interceptor to negate the real weapons expected there, which could reduce the required number to a factor of ≈ 10 below that for midcourse defenders with poor discrimination. Since the expected targets for such time-urgent weapons would be missiles, airbases, and communications, the number required would be in the hundreds. They would, moreover, provide some disincentive to the destabilization caused by those submarine missiles in the first place.

B. Unauthorized/Rogue Launch

Unauthorized launches could be similar in size to accidental launches, although it can be argued that if a launch control team could release one missile without authorization, it could probably fire a whole complex of ≈ 10. To the extent that the control over and the launching of missiles were centralized at levels higher than such complexes, the number of missiles that might be launched without authorization would increase accordingly.

All defenses would be stressed much as they would be by an accidental launch. The main difference would be the involvement of an individual or group committed to the execution of launches, which could make their occurrence much more likely than that of accidental launches. Destruct-after-launch concepts would become more complicated, because a group capable of launching one or more missiles without authorization would presumably be capable of disarming their destruct mechanisms as well.

C. Third-Country or Subnational Launches

Third-country launches executed by a fanatic or irrational leader would not be susceptible to deterrence through the threat of retaliation. For launches by subnational groups, it might not even be possible to identify which group to retaliate against. Nuclear weapon, design, and launcher technology are diffusing worldwide. Thus, the probability of third-country and subnational launches will presumably grow with time.

Such launches should, for some period of time, involve one or a few missiles, a few weapons per missile, and few penetration aids. Launched from abroad, such simplified threats should be less stressing than accidental or unauthorized launches, but the weapons would probably be aimed at cites, whereas accidental or unauthorized launches would be aimed at military targets. Defenses would be required; other means of destruction are unlikely.

At present, such a nuclear weapon could be delivered by placing it on a ship, sailing it into the harbor of a large city,

and exploding it. At present there are no defenses against such attacks. If, however, defenses against missile delivery were developed, the incentive would increase to develop defenses against other existing vulnerabilities. The U.S. eliminated its air defenses because they could be destroyed by missiles. If there were limited missile defenses, air defenses could and probably should be resumed. Similarly, if third-country and subnational missile launches were addressed, there would be more of an incentive to defend against sea and land deliveries.

Against launches from the third country itself, boost-phase and midcourse defenses should be very effective against undecoyed or lightly decoyed threats. Boost-phase defenders should have adequate warning from existing assets. Their scaling would be as for single land missile launches, i.e. ≈ 5-10 defenders. For midcourse defenders, improved warning would be useful, but the main issue would appear to be upgrading existing radars, which would be their primary means of establishing track. A combination of boost and midcourse defenders would average over the weakness of the sensors as well as reduce the probability of a weapon reaching a value target.

Against launches from a ship in midocean or close to shore, the spectrum of defenses narrows. Such launches are not discounted; if such a launch could be executed, it could be depressed. In that case, the technical issues would remain as before. The main difference would be the lack of decoys and the single weapon. Both would reduce the number of interceptors required, but they would probably have to be terminal and deployed around each major urban area.

D. Summary

Accidental, unauthorized, third-country, and subnational launches are linked, because the current logic of deterrence through the threat of retaliation does not operate on any of them.[43] Irrational components, individuals, or groups cannot be deterred rationally, it is necessary to defend against them.

IV. DEFENSES

Under extreme circumstances, e.g., breakthroughs or reverses in theater conflict, deliberate attacks on the U.S. might not appear irrational. The attacks could range from strikes with limited objectives, damage, and numbers of weapons to large-scale exchanges. This section progresses from the requirements for defense against limited attacks through those for stressing attacks on missiles and other elements.

A. Limited Attacks

Limited attacks have primarily been discussed in the context of disrupting rapid reinforcement of theaters, principally Europe. For that, the number of embarkation sites is limited, so the sites could be struck precisely and with limited collateral damage to reduce the likelihood of counter strikes. While the requirement for defense against such attacks seems remote today, that perception could reverse as quickly as it developed.

Without defenses, the number of weapons required to isolate the U.S. from Europe could be on the order of a dozen. With defenses, the number could increase to a level at which the benefit from interrupting reinforcements would no longer justify the risk of such attacks. Defenses against limited attacks would differ from the limited protection discussed above in that they would act rationally to make more credible the threat of retaliation, which would restore the effectiveness of deterrence by that means.

Other targets are possible. The attacker could strike key command, control, and communication facilities to render our forces useless, which could also be done with a modest number of missiles and limited collateral damage. In such attacks, submarines close to shore are of particular concern because of their missiles' short flight times to coastal bomber bases. When submarines attain a hard-target capability, they will present a threat to land-based missiles; with more timely communications, they could also address inland bomber bases and mobile missiles in garrison or that depended on warning.

Limited attacks could be comparable in size to the accidental or unauthorized attacks discussed above, but they would add the elements of technological sophistication and integrated planning. In practice, that would mean capable and intelligently planned attacks with a full complement of penetration aids and mix of systems. One component of it, cruise missiles, is not addressed by current strategic defense research. The missile threat could be addressed by extensions of the boost and midcourse technologies discussed above. The number of missiles required might be in the range of 1-10, so 10-100 boost phase defenders, or a comparable number of midcourse interceptors with moderate discrimination capability, could severely impact the threat.

If the price to attack could be raised by a factor of 2-3, it would no longer be limited in any sense. Thus, against ICBMs, the cost of the defense could be a few billions of dollars. SLBMs would be a logical means of executing the time sensitive parts of the attack. Since a knowledgeable adversary would be aware of the intrinsic limitations of the current systems discussed above, it can be assumed that much of that threat would be inaccessible to current boost and midcourse systems. Addressing those limitations would be more a matter of program redirection than cost. Limited defenses seek to reinforce rational deterrence by raising the threshold for successful attack to a level at which the attacker would find the likelihood and extent of retaliation outweighed the gains from executing the attack.

B. Defense of Fixed Missiles

Undefended Minutemen or MXs in garrison could be destroyed by a modest number of RVs. Quoted accuracies of a few hundred meters suggest that in the near future weapons might have kill probabilities $q \approx 0.8$ against even hardened silos. If so, an attack by $M \approx 400$ missiles with $m \approx 10$ weapons each, or $mM \approx 4{,}000$, roughly the current Soviet inventory of first-wave hard-target-killing weapons, on $N \approx 1{,}000$ Minutemen would give

$S \approx N(1-q)^{mM/N}$ survivors. For mM, the number of survivors would be ≈ 2, which is insignificant. For MXs in garrison on $N = 7$ bases, $mM/N \approx 4{,}000/7 \approx 600$, which should leave no survivors. Hardening would not help; active defenses or mobility would be required. Boost, midcourse, or terminal defenses could be used.

Boost-layer defenses are random, so K defenders, of which a fraction f were available, would reduce the threat by about fK missiles. For K small, their contribution would be negligible, but for $fK = \epsilon M$, the number of penetrating weapons would be reduced to $m(1-\epsilon)M$, for which the number of surviving missiles would be $S \approx N(1-q)^{m(1-\epsilon)M/N}$. For $\epsilon = 1/2$, $S \approx 1{,}000(0.2)^2 \approx 40$, which could be useful. For $\epsilon = 3/4$, $m(1-\epsilon)M \approx 1{,}000 \approx N$ and $S \approx N(1-q) \approx 200$. For MXs garrisoned on 7 bases and $\epsilon = 3/4$, $S \approx 7(0.2)^{1{,}000/7} \approx 0$, which is no improvement. In the near term, achieving $fK = M/4$ would require $K \approx M/4f \approx 5M/4 \approx 500$ defenders; $fK = M$ would take about 2,000. In the midterm, they would take $\approx 400/4 \cdot 0.07 \approx 1430$ and 6,000, respectively.

Preferential defenses would do better, but they require multiple aimpoints for leverage. Minuteman has $N \approx 1{,}000$ aimpoints, so $I \approx 2{,}000$ interceptors could defend $S \approx NI/mM \approx 1{,}000 \cdot 2{,}000/4{,}000 \cdot \approx 500$ missiles and $\approx 1{,}000$ weapons, in accord with Fig. 1. For 50 MXs garrisoned on 7 bases, 2,000 midcourse interceptors should be able to defend $\approx 7 \cdot 2{,}000/4{,}000 \cdot \approx 3.5$ bases or 35 missiles with 350 weapons. It is possible that 7 sites on one base separated by ≈ 10 km would perform about as well.

Even a treaty-compliant preferential defense with $I = 100$ interceptors should be able to protect a fraction $I/mM \approx 100/4{,}000 \approx 2.5\%$ of the targets defended. For Minutemen, that would amount to 25 missiles with 50 weapons; for MXs it would amount to ≈ 1 missile with 10 weapons. The reason for the difference is the larger number of aimpoints for Minutemen than MXs in garrison.

An adaptive preferential defense would do significantly better. It would, however, need some boost phase defense to break up the attack. If a near-term boost-phase defense was about 30% effective (i.e., $fK \approx 0.3 \cdot M$ or $K \approx 0.3 \cdot 500/0.2 \approx 750$),

about 35% of the Minuteman silos would be attacked by ≤ 2 penetrating weapons. The average number of interceptors needed to protect each would be about 0.6 per silo, so $I \approx 600$ interceptors could protect about 350 Minutemen.[44] That is about $350/600 \approx 0.58$ survivors per interceptor as contrasted to $500/2{,}000 = 0.25$ with nonadaptive preferential defenses. Thus, for modest boost-phase defenses, adaptive preferential defenses could be about 2.3 times more effective, if their requirements for timely information on which silos had few penetrating weapons could be met. The difference between preferential and adaptive defenses is primarily the difficulty of providing sensors that can detect and track cold, surviving weapons in midcourse. The interceptors would be essentially the same.

These results are sensitive to decoys. If there were 10 undiscriminated decoys per RV, the defense would be degraded by a factor of ≈ 10, as shown by Figs. 3 and 4. Figure 5 shows that in the midterm ≈ 150 Minutemen would survive a 2,000-weapon attack with 20 decoys per weapon but that only ≈ 30 would survive a similarly decoyed attack with 6,000 weapons. If a number of $S \approx 100$ missiles is taken to represent a useful deterrent, it would be necessary for the defense to discriminate down to ≈ 10 decoys per weapon to be effective, which the technologies discussed in Section II could apparently do. It would probably be necessary because the attacker probably could provide ≈ 100 decoys per weapon in the midterm.

The analysis of Section II.D can be used to determine the appropriate combination of boost and midcourse defenses for any threat configuration. Crudely, for ≥ 20-30 deployed decoys, boost-phase defenders would be essential and would be used if their costs were no greater than 2-3 times that of the midcourse interceptors. For fewer decoys or more expensive defenders, however, boost-phase defenders would not be deployed; instead, midcourse interceptors could be used to achieve survivability levels $\approx D^{-1}$ times the undecoyed results above.[45] Adaptive preferential defenses work in the same way with decoys and could retain their advantage in effectiveness, although the number of

interceptors required would increase in proportion to the number of undiscriminated decoys.[46]

In estimating the performance of defenses against the nominal attacks discussed above, it was assumed that the full number of hard-target killers fell on each target set. The attacker would actually allocate his weapons over all target sets in order to maximize damage on all of them. That would reduce the number of weapons allocated to each target set, which would reduce the damage to them. For preferential defense of Minuteman and MX the optimal allocation would target about four times as many weapons on Minuteman as on MX, in accord with the number of retaliatory weapons carried; the defenses would be located accordingly.[47] For the 4,000-weapon attack discussed above, the number of surviving Minutemen would be about $1{,}000 \cdot 1{,}500/3{,}000 \approx 500$ with 1,000 weapons, and the number of surviving MXs would be about $7 \cdot 500/1{,}000 \approx 3.5$ sites with 24 missiles and about 240 weapons, for a total of about 1,240 retaliatory weapons.

C. Defense of Mobile Missiles

Mobility essentially generates additional aimpoints cheaply. Moving Midgetman away from known positions or MX out of its garrisons and dispersing it over the full rail network could take tens of minutes or days, respectively. Thus, the survivability of Midgetman could start at a modest level and then grow rapidly in tens of minutes after warning, and that of MX in garrison without active defenses would start low and grow over a period of a few days. The previous section treated the scaling of the defenses for fixed missiles. This section treats them when fully mobile. Intermediate cases can be treated approximately by interpolation.

Deployed on a range of effective radius ≈ 300 km, hard-carry Midgetmen with lethal radii of ≈ 3 km would have $\approx (300/3)^2 = 10^4$ aimpoints to hide in. Thus, a Soviet first wave of 6,000 ICBM RVs plus 4,000 SLBM RVs, or a total of 10,000 RVs, would be just strong enough to cover each aimpoint.[48] For what would essentially be low-accuracy pattern bombing, SLBMs could be used.

Even with minimal communication they should be sufficiently timely and accurate for mobiles; they might not be for other targets.

There are, however, other requirements for RVs. They would be allocated to various target sets roughly in proportion to their weapon-equivalent values.[49] Two RVs on each of 1,000 Minuteman silos would take about 2,000 RVs, about 4 on each of 50 bomber bases, and a like number of C^3 sites would take another $\approx$ 500. All together, $\approx$ 2,500 RVs might be diverted from this nominal attack on the mobiles, which would leave $\approx$ 10,000-2,500 $\approx$ 7,500 RVs available to cover Midgetman aimpoints. If so, $\approx$ 7,500/10,000 = 75% of the Midgetmen aimpoints could be struck, in which case of 500 Midgetmen about 0.25 x 500 = 125 missiles and RVs would survive.

Midgetman survivability is largely geometric; it could be increased significantly by increasing the size of its range. Increasing its radius threefold would increase its area, and hence the number of aimpoints by an order of magnitude, which would increase its survivability beyond the capability of any blind attack. If after alert the Midgetmen were allowed to move out of the original range, their survivability would grow quadratically with time. If, however, they remained on a fixed range, or for the time it took to move out the additional $\approx$ 1,000 km, Midgetman survivability would saturate at the $\approx$ 25% level estimated above.

MXs would have $\approx$ 200,000 km of rails over which to disperse for survivability, of which perhaps half would be far enough from cities to be useful. If each RV could clear $\approx$ 10 km of track, MXs would have $\approx$ 10,000 aimpoints to hide in, which is about the same number as for the Midgetmen. Mobiles on commercial rails, however, face an additional concern about loss of deception. If human or mechanical means could determine and transmit the information that one of the $\approx$ 10 MX trains was on a 100- to 1,000-km section of the line, the attacker could eliminate it with 10 to 100 weapons or 1-10 missiles, in which case 1-10% of the attack could eliminate all 10 MX trains. Given the openness

of U.S. society, it is not clear that it would be possible to eliminate all such means of localization prior to attack.

The above estimates indicate that in the absence of defenses, in a surprise attack on 500 Midgetman, 500 MX, 1,000 Minuteman, and 200 bombers, only about 25% of the Midgetmen, or $\approx$ 125 RVs, would survive. With a few days warning, MXs could probably double the number of mobile aimpoints. That should roughly double the number of surviving RVs to $\approx$ 200-300 RVs, which together with some fraction of the bombers could be adequate for retaliation.

These results, however, are sensitive to variations in the threat. If the Soviets could hide as many land missiles in forests or warehouses as were in the visible threat, they could cover most MX and Midgetman aimpoints plus the fixed and bomber targets. The missiles would not need much accuracy, so their components could be manufactured apart from normal facilities and need not be tested conventionally. They would not need complicated launchers; prelaunch survivability is not a requirement for first-strike weapons.

Defenses are less sensitive to such variations. Boost-phase defenses would randomly subtract RVs. For fewer attacking RVs than aimpoints, each intercept would remove $m \approx 10$ RVs, which would increase the number of safe aimpoints by a like amount, which would increase survivability by about 10/10,000 $\approx$ 0.1%, or about 1 Midgetman. Consequently, 2,000 space defenders could, in the near term, reduce the threat by $\approx 2{,}000 \cdot 0.2 = 400$ missiles, or 4,000 RVs. If the first wave had about 10,000 RVs, 4,000 were removed in boost and 2,500 were used for silos, bombers, and command targets, then about 3,500 would be available for 20,000 Midgetman and MX aimpoints, which would increase their survivability to $\approx 1 - (3{,}500/20{,}000) \approx 83\%$.

Preferential defense would not increase these values unless the position of the mobile missiles and the disposition of the threat were known. In the limit, the analysis is clear. If the interceptors knew where each Midgetman was, they could destroy any RV aimed toward those sites. With the boost overlay

discussed above, there would be 3,500 RVs attacking the 20,000 mobile aimpoints, but only about 500 + 10 sites would be occupied. Thus, only $3{,}500 \cdot 510/20{,}000 \approx 90$ sites would have to be defended, which could be done by about 90 interceptors. That would defend all of the mobiles, their 550 launchers, and 1,000 weapons and give $\approx 550/90 \approx 6$ surviving launchers per interceptor, which illustrates the additional leverage in preferentially defending multiple aimpoints. The timelines, information, and accuracy for such defenses would, however, be more stringent.

Boost-phase defenses could eliminate submarine-launched missiles altogether, because constellations that were sized for ICBMs would generally be oversized to negate submarine launches from port, bastion, or offshore patrol. The suppression of close-in submarines was discussed on pp. 15-16.

With midcourse defenders, a mix, in which the boost-phase defenders thinned the overall threat and the midcourse interceptors defended silos and other targets preferentially could be useful. For 4 RVs per silo of kill probability 0.8, an undefended fixed missile's probability of survival would be $0.2^4 \approx 0.0016$, so ≈ 3 RVs should survive. With a 30% boost-phase defense and 2,000-interceptor preferential defense, about 500 missiles and 1,000 RVs should survive. With a 2,000-interceptor adaptive preferential defense, about 1,500 should survive. With 4,000 RVs devoted to silos and about 1,000 to bombers and other targets, about 5,000 would remain for mobile targets, of which about 75% should survive. Thus, with a mixed defense of $M/f \approx 0.3 \cdot 1{,}000/0.2 \approx 1{,}500$ boost-phase and 2,000 midcourse defenders, about 75% of the overall retaliatory assets should survive. The attacker would lose 10,000 weapons; the defender, about 750, which would eliminate any military benefit from the attack.

D. Command, Control, Communication (C^3) and Other Targets

The C^3 networks have 50-100 nodes but require continuity of the paths through them for effectiveness. Without defenses, the probability of any node surviving a 400-RV attack on the network would be negligible, because against lightly hardened nodes, the

RVs' kill probability should be near unity. If random boost-phase defenses could attrit the attack by 70%, there would still be about 1 RV per node. Some would survive on statistics, but the probability of a 10-node link surviving would be negligible. Thus, active, preferential defenses would be required to preserve C^3. For a 400-RV undecoyed attack on 100 nodes with ≈ 10 independent paths, a preferential defense with 100 interceptors could protect ≈ $10 \cdot 100/400$ ≈ 2 paths. To maintain that level against an attack with 10 decoys per RV would require about 10 times as many interceptors, or ≈ 1,000, which roughly bounds the defenses within attainable levels.

There are some targets, such as the National Command Authority (NCA), that have few aimpoints. For such targets, it would be necessary to match weapons with interceptors one on one. Thus, an adversary willing to pay a high price could always overwhelm such a target, particularly since a highly structured, decoyed attack with both missile and airborne weapons could be used. Currently, the solution is to transfer command to an airborne commander, should the primary authority be lost. Because airplanes generate very large numbers of aimpoints, their mobility should protect them as long as they are aloft. An alternative would be to proliferate the primary NCA to ≈ 10 remote, hardened sites. If that was done, the previous example shows that about 100 preferential interceptors could protect about 2 of the sites from ≈ 400 undecoyed weapons. Adaptive commitment could save about a factor of 2 more.

E. Progression

The above examples indicate that defenses' performance increases with the number of defenders, the degree of adaptation, and the extent of discrimination. The increases do not appear to saturate short-of-capable defenses against all military attacks. The level of defense would vary for the different target sets over time. Midgetman survivability would appear to be affected earliest; alert bombers, next; and the MX, third. The other targets have fewer nodes, higher values, and are susceptible to

more modes of attack. As to the missile attack, however, as competent defenses were deployed for missile launchers, other defenses would become available to compensate for the intrinsic vulnerabilities of other targets.

As deployments continue to increase above the levels discussed above, the overall survivability of the defender should increase. The main impediments to that are decoys and boost-phase absenteeism. If discriminants can be developed that keep the number of undiscriminated decoys to the level of 5-10 per weapon, decoys should not be a barrier. Absenteeism primarily affects kinetic-energy defenders. At some point, absenteeism could stress even the least expensive defenders. Before that point, however, directed-energy defenses, which could have almost an order of magnitude advantage over kinetic-energy defenders, should be available. Then directed energy could either phase in or be used in concert with defenders to provide a low-cost, very low-leakage boost phase.

The long-term configuration would thus appear to be a very effective boost phase with roughly the same number of effective defenders as missiles, which corrected for absenteeism could be $\approx$100,000 defenders. With a combined kinetic- and directed-energy boost phase, the overall effectiveness could be well over 95%, so the midcourse could be required to address $\approx$ 5% of the missiles, or $\approx 10 \cdot 0.05 \cdot 1{,}000 \approx 500$ RVs and $\approx$ 5,000 decoys, which would at worst require a like number of interceptors.

F. Summary

Under extreme circumstances, attacks on the U.S. might not appear irrational. They could range from strikes with limited objectives, damage, and numbers to an attempt to negate major strategic forces. Limited defenses seek to reinforce deterrence by raising the threshold for success. The land-missile component of such attacks could be addressed with current technology; close-in submarines would be more stressing.

Undefended fixed missiles could be destroyed by a modest number of RVs. Boost-layer defenders could help the Minuteman

but not the MX; a few thousand preferential interceptors could save enough of each for retaliation. Adaptive defenses could save enough for reasoned response. All are sensitive to the number and quality of decoys.

Mobility generates additional aimpoints. The Midgetman and MX could each generate about 10,000. After allocating RVs to bombers and other targets, the remainder could permit about 25% of the mobiles to survive. With a few thousand interceptors, most mobiles could survive, absent unaccounted attackers. Mixes of boost and midcourse defenses, while not generally optimal, could be very effective in defending both fixed and mobile missiles.

The C^3 networks require continuity, but if they have some significant number of independent paths, they can be defended preferentially. Some targets, such as the NCA, have few aimpoints, so an adversary willing to pay a high price could always overwhelm them, particularly with structured, mixed attacks. Proliferation of sites could offset that vulnerability.

In these examples, it is clear that the performance of the defenses increases with the number of defenders, the degree of adaptation, and the extent of discrimination. The increases are roughly proportional, and would not appear to saturate until the defenses reached levels that were very capable against all military attacks. With larger deployments, the development of improved discriminants, and the admixture of directed energy, practical defenses could reach the levels required to eliminate the military effectiveness of large attacks and approach the levels required to provide adequate protection for value targets.

V. CONCLUSIONS

Previous antiballistic missile programs emphasized the importance of survivability and feasibility; their lessons have been learned. The current issues are performance and cost. Midcourse defenses face discrimination problems; space-based layers face cost and survivability concerns. There is, however, an adequate spectrum of potentially effective defensive concepts

to address those concerns. The boost layer is attractive because many weapons and decoys can be killed per intercept. Midcourse interceptors are cheap, given discrimination. Simple models indicate that their initial deployment should be effective and affordable; later developments should improve the effectiveness of each.

There are no formalized missions below phase one, but there are limited threats that are significant, tractable to limited defenses, and immune to current deterrence through the threat of retaliation. Despite safety mechanisms, an accidental launch could occur. It would present a threat that was a factor of 10-1000 less than that defenses could face, but it could still be stressing if each missile had multiple weapons and penetration aids, as expected. Existing technologies should suffice; the cost of a few tens of ground-based interceptors would be small compared to the damage expected in their absence.

Unauthorized launches could be similar or larger. Destruct-after-launch defenses would probably not apply; a group capable of launching missiles without authorization could presumably disarm them. Third-country launches executed by fanatic or irrational leaders would not be susceptible to deterrence through the threat of retaliation. Their probability should grow with time. Irrational components, individuals, or groups cannot be deterred; it is necessary to defend against them. Under extreme circumstances, such as reverses in theater conflict, deliberate attacks on the U.S. might not appear irrational. If the price to attack successfully could be raised by a factor of 2-3, it would no longer be limited in any sense. That appears feasible with current interceptor technology.

Undefended Minutemen or MXs in garrison could be destroyed by a modest number of RVs. Boost, midcourse, or terminal defenses could address that weakness. Preferential defenses would do better, but they would require multiple aimpoints for leverage. Adaptive preferential defenses could be about 2.3 times more effective, if their information requirements could be met. Mobility can generate additional aimpoints cheaply, but the

first wave could be strong enough to cover most of their aimpoints. In a surprise attack, absent defenses, about 25% of Midgetman, or ≈ 125 RVs, would survive. Even that level is sensitive to hidden missiles. A mix could be useful in which the boost-phase defenders thinned the overall threat, and the midcourse interceptors defended silos and other targets preferentially.

The C^3 networks have long paths whose continuity is required for effectiveness. Without defenses, the probability of any node, let alone a whole path, surviving would be negligible. Maintaining paths against attack would require a few hundred to one thousand interceptors, which is within attainable levels. Targets such as the NCA have few aimpoints; an adversary willing to pay a high price could always overwhelm them. But with modest proliferation, they could be protected by similar numbers of interceptors.

The defenses' performance increases with the number of defenders, degree of adaptation, and extent of discrimination. These increases do not appear to saturate less-than-capable defenses against military attacks. The long-term configuration could be a very effective boost phase with roughly the same number of effective defenders as missiles. With a kinetic- plus directed-energy boost layer, effectiveness could be over 95%. If so, midcourse could be required to address about 5% of the missiles, or about 500 RVs and 5,000 decoys. Both layers appear feasible. Determining strategic defenses' ultimate effectiveness could require a decade of research, development, and testing. When defenses will be needed depends on external developments over which we have little direct control. Effective defenses would, however, provide both a hedge against uncertainty and a positive incentive for the reduction of offensive forces.

REFERENCES

1. F. Ikle' and A. Wohlstetter, Discriminate Deterrence, Report of the Commission on Integrated Long-Term Strategy (Washington, DC, U.S. Government Printing Office, January 1988).

2. G. Canavan, "SDI: Is Its Future Past?," Los Alamos National Laboratory document LA-11782-MS, November 1989; debate with R. Garwin at the Council on Foreign Relations, Washington, DC, 20 November 1989.

3. J. Abrahamson, "Technologies for Effective Multilayer Defenses," A. Wohlstetter, F. Hoffman, and D. Yost, Eds., Swords and Shields (Lexington, Boston, 1987).

4. G. Yonas, "Strategic Defense Initiative: The Politics and Science of Weapons in Space," Physics Today, June 1985, pp.24-32.

5. J. Gardner, E. Gerry, R. Jastrow, W. Nierenberg, and F.Seitz, Missile Defense in the 1990s (Washington, Marshall Inst., 1987).

6. R. Garwin, "How Many Orbiting Lasers for Boost-Phase Intercept?" Nature, 315, 23 May 1985, pp. 286-90.

7. G. Canavan, "Directed Energy Architectures," Los Alamos National Laboratory report LA-11285-MS, March 1988; Proceedings "SDI: the First Five Years," Institute for Foreign Policy Analysis, Washington, DC, 13-16 March 1988.

8. G. Canavan and A. Petschek, "Concentration of Defensive Satellite Constellations," Los Alamos National Laboratory document LA-UR-88-3510, October 1988.

9. G. Canavan, "Scaling Kinetic Kill Boost-Phase Defensive Constellations," Los Alamos National Laboratory report LA-11331-MS.

10. L. Wood, "Brilliant Pebbles and Ultravelocity Slings: A Robust, Treaty-Compliant Accidental Launch Protection System," Lawrence Livermore National Laboratory report UCRL (draft), 28 May 1988.

11. G. Canavan, "Directed Energy Architectures," op. cit.

12. O. Judd, private communication, SDIO, 17 November 1989.

13. L. Wood, "Brilliant Pebbles and Ultravelocity Slings: A Robust, Treaty-Compliant Accidental Launch Protection System," op. cit.

14. G. Canavan, "Transitional Strategic Defense Architectures," Los Alamos National Laboratory report LA-11524-MS.

15. K. Gottfried and H. Kendall, "Space-Based Missile Defense," Union of Concerned Scientists report, March 1984.

16. G. Canavan and A. Petschek, "Satellite Allocation for Boost Phase Missile Intercept," Los Alamos National Laboratory report LA-10926-MS, April 1987.

17. R. Garwin, K. Gottfried, and H. Kendall, The Fallacy of Star Wars (New York, Vintage Books, October 1984).

18. G. Canavan, "Free Electron Lasers in Strategic Defense," Los Alamos National Laboratory report LA-11225-MS, March 1988.

19. H. Bethe, R. Garwin, K. Gottfried, and H. Kendall, "Space-Based Ballistic Missile Defense," Scientific American, 251(4), October 1984, pp. 39-49.

20. G. Canavan, "Directed Energy Concepts for Strategic Defense," Los Alamos National Laboratory report LA-11173-MS, June 1988.

21. G. Canavan and A. Petschek, "Satellite Allocation for Boost Phase Missile Intercept," Los Alamos National Laboratory report LA-10926-MS, April 1987.

22. G. Canavan and A. Petschek, "Satellite Allocation for Boost Phase Missile Intercept," op. cit., p. 28.

23. N. Bloembergen and C. Patel, "Report to the American Physical Society of the Study Group on Science and Technology of Directed Energy Weapons," Reviews of Modern Physics 59(3), part II, July 1987.

24. G. Canavan, "Constellation Sizing for Modest Directed Energy Platforms," Los Alamos National Laboratory report LA-11573-MS, June 1989.

25. G. Canavan, N. Bloembergen, and C. Patel, "Debate on APS Directed-Energy Weapons Study," Physics Today, 40(11), November 1987, pp. 48-53.

26. G. Canavan, "Role of Free Electron Lasers in Strategic Defense," Los Alamos National Laboratory document LA-UR-5, 1 January 1990.

27. G. Canavan and E. Teller, "Survivability and Effectiveness of Near-Term Strategic Defenses," LA-11345-MS, January 1990; "Strategic defence for the 1990s," Nature, Vol 344, pp. 699-704, 19 April 1990.

28. G. Canavan and J. Browne, "Roles for Neutral Particle Beams in Strategic Defense," Los Alamos National Laboratory report LA-11226-MS, April 1988.

29. R. Garwin and H. Bethe, "Anti-Ballistic-Missile Systems," Scientific American, March 1968, pp.21-31.

30. G. Canavan, "Directed Energy Weapons-Lasers: Ground and Space Based Systems," Los Alamos National Laboratory report LA-11557-MS, June 1989; J. Davidson, ed., Handbook of Strategic Defense, American Institute of Aeronautics and Astronautics.

31. G. Canavan, "Neutral Particle Beam Popup Applications," Los Alamos National Laboratory report LA-11785-MS.

32. J. Cooper, C. Pena, and K. Bue, "How Defenses Work and the Implications for Strategic Defense Architectures," SRS Technologies Technical Note TN-MA-87-001, August 1987.

33. G. Canavan, "Adaptive Preferential Defense and Discrimination," Los Alamos National Laboratory report LA-11375-MS, October 1988, Fig. 7.

34. A. Carter and D. Schwartz, Eds., Ballistic Missile Defense, (Washington, the Brookings Institution,1984).

35. G. Canavan, "Nuclear Effects on Strategic Defense Sensors," Los Alamos National Laboratory document LA-UR-87-2986, 22 September 1987.

36. G. Canavan, "Adaptive Preferential Defense and Discrimination," op cit., pp. 16-19.

37. G. Canavan, "Discrimination: Who Needs It?," Los Alamos National Laboratory report LA-11917-MS, July 1990.

38. G. Canavan, "Analysis of Combined Boost and Midcourse Defenses," Los Alamos National Laboratory document LA-UR-4233, 14 December 1989.

39. R. Garwin, "Prospects for Strategic Defense," Proceedings, Fifth Annual Symposium, United States Space Foundation, Colorado Springs, Colorado, 6 April 1989.

40. G. Canavan, "Goals for Limited Strategic Defenses," Los Alamos National Laboratory report LA-11419-MS, May 1989.

41. T. Postol, "Implications of Accidental Launch Protection Systems for US Security," Statement before the HASC Panel on SDI, 20 April 1988; New Scientist, 21 April 1988, p. 25.

42. G. Canavan, "Goals for Limited Strategic Defenses," op. cit., Fig 2.

43. G. Canavan, "Goals for Limited Strategic Defenses," Los Alamos National Laboratory report LA-11419-MS, May 1989.

44. G. Canavan, "Adaptive Preferential Defense and Discrimination," op cit., Figs 3 and 5.

45. G. Canavan, "Analysis of Combined Boost and Midcourse Defenses," Los Alamos National Laboratory report LA-11780-MS, December 1989.

46. G. Canavan, "Adaptive Preferential Defense and Discrimination," op cit., pp. 9-12.

47. G. Canavan, "Optimization of Midcourse Attack and Defense Allocations," Los Alamos National Laboratory report, LA-draft-MS, December 1989.

48. Soviet Military Power: An Assessment of the Threat (U.S. Department of Defense, Government Printing Office, 1988).

49. G. Canavan, "Optimization of Midcourse Attack and Defense Allocations," op. cit.

Fig.1. Preferential Defenses Near Term

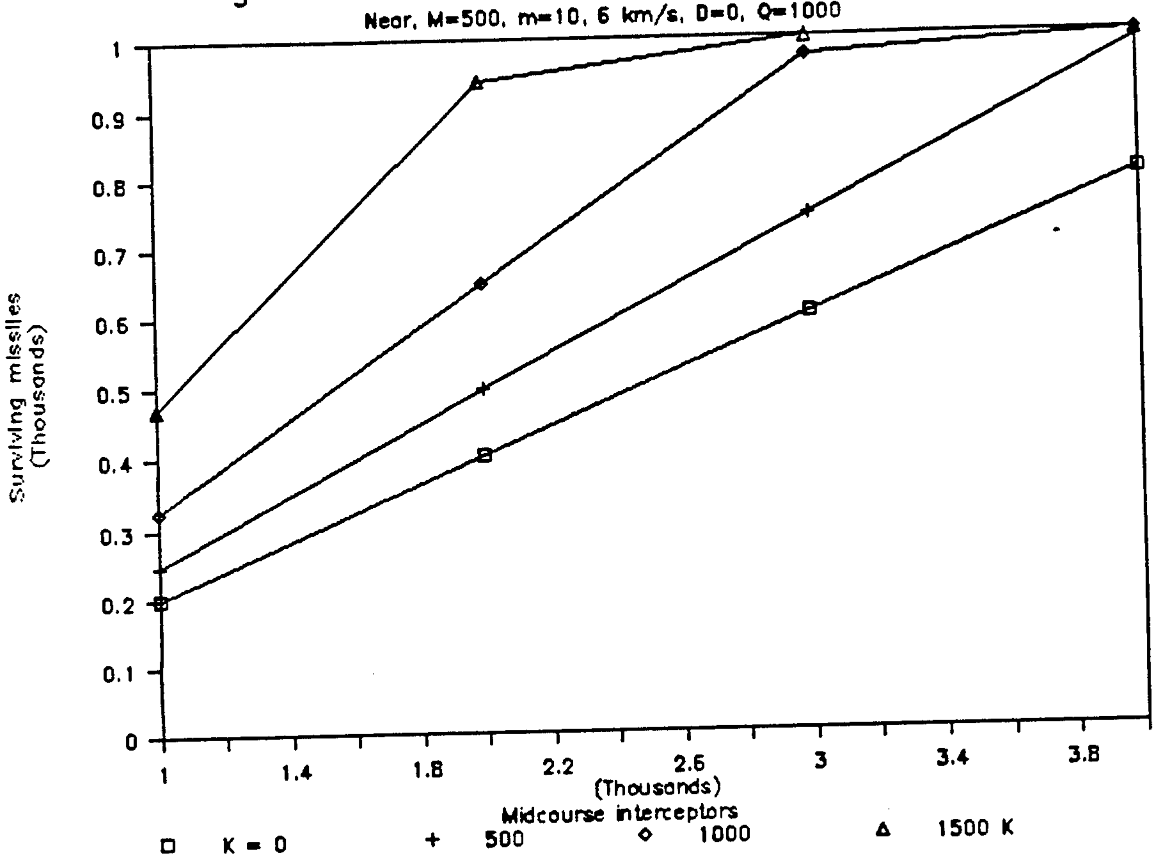

Fig.2. Preferential Defenses Midterm

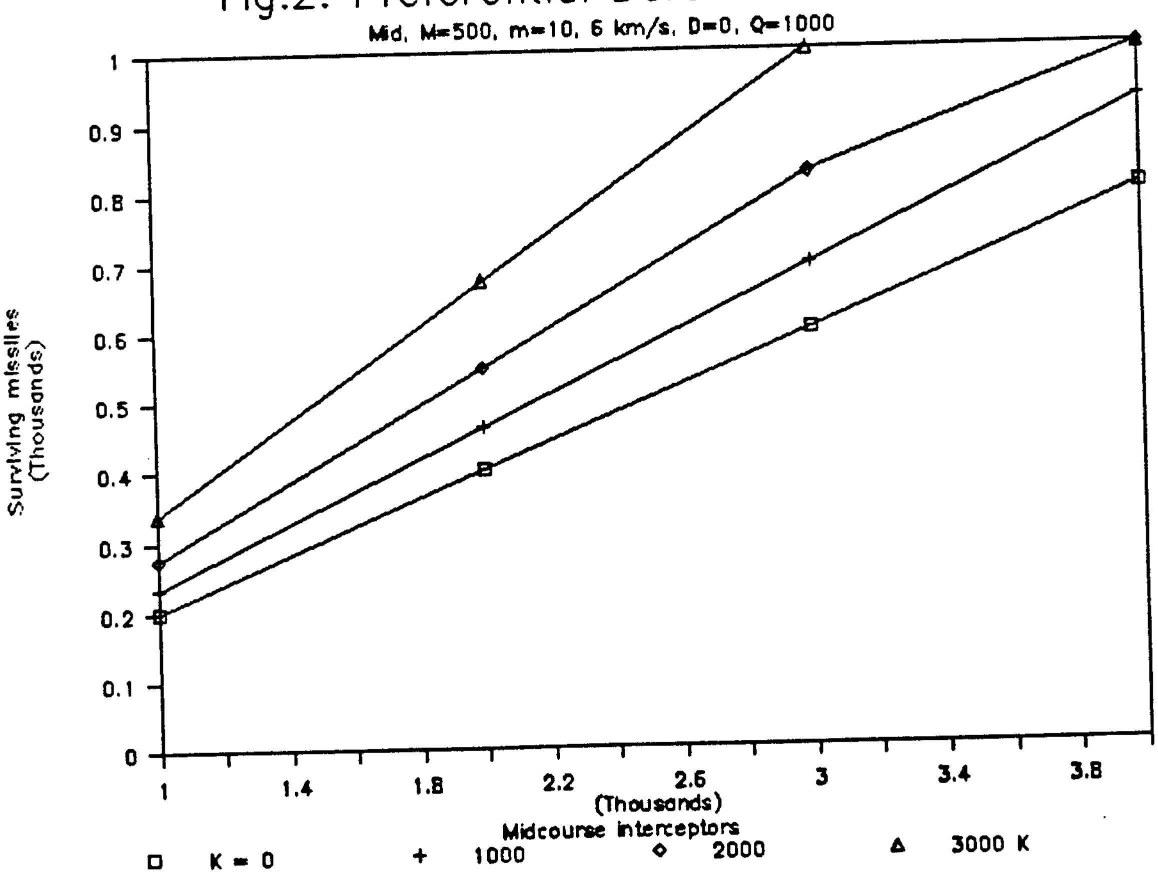

Fig.3. Pref Defense Near with Decoys

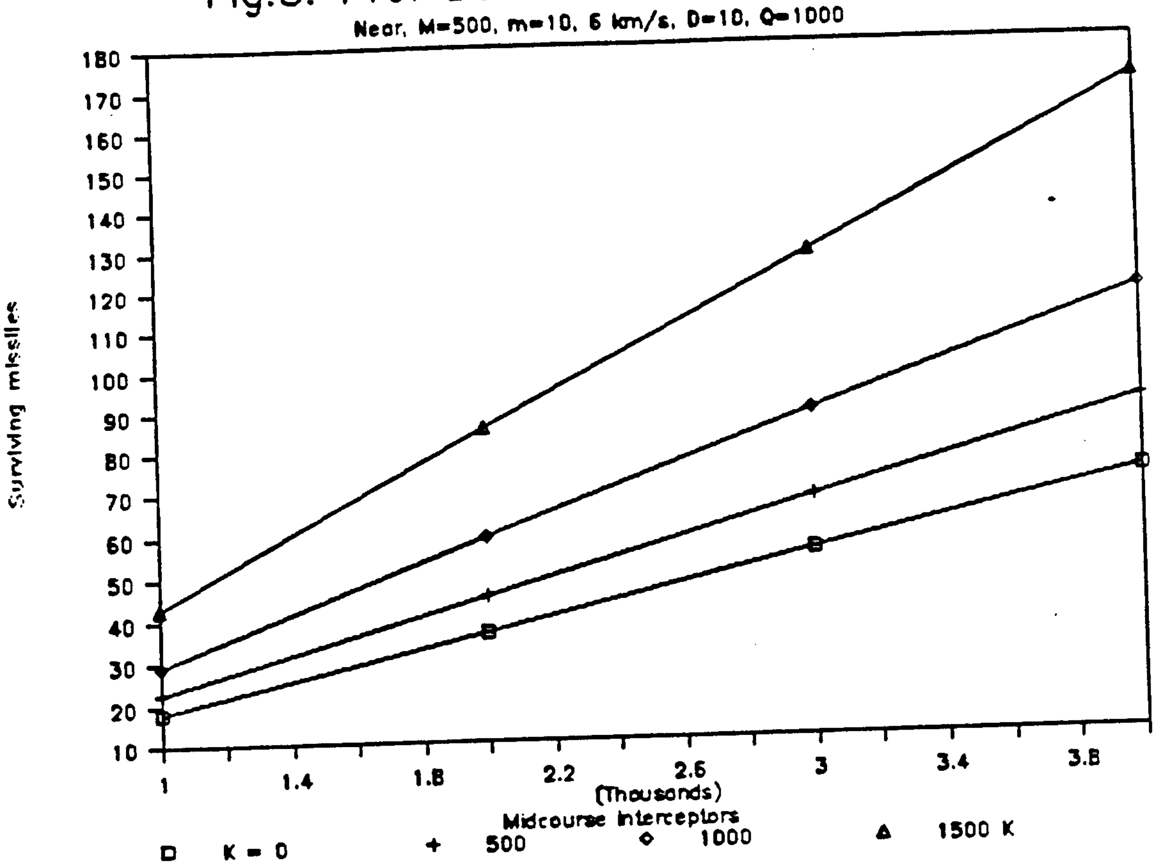

Fig.4. Pref Defenses Midterm with Decoy

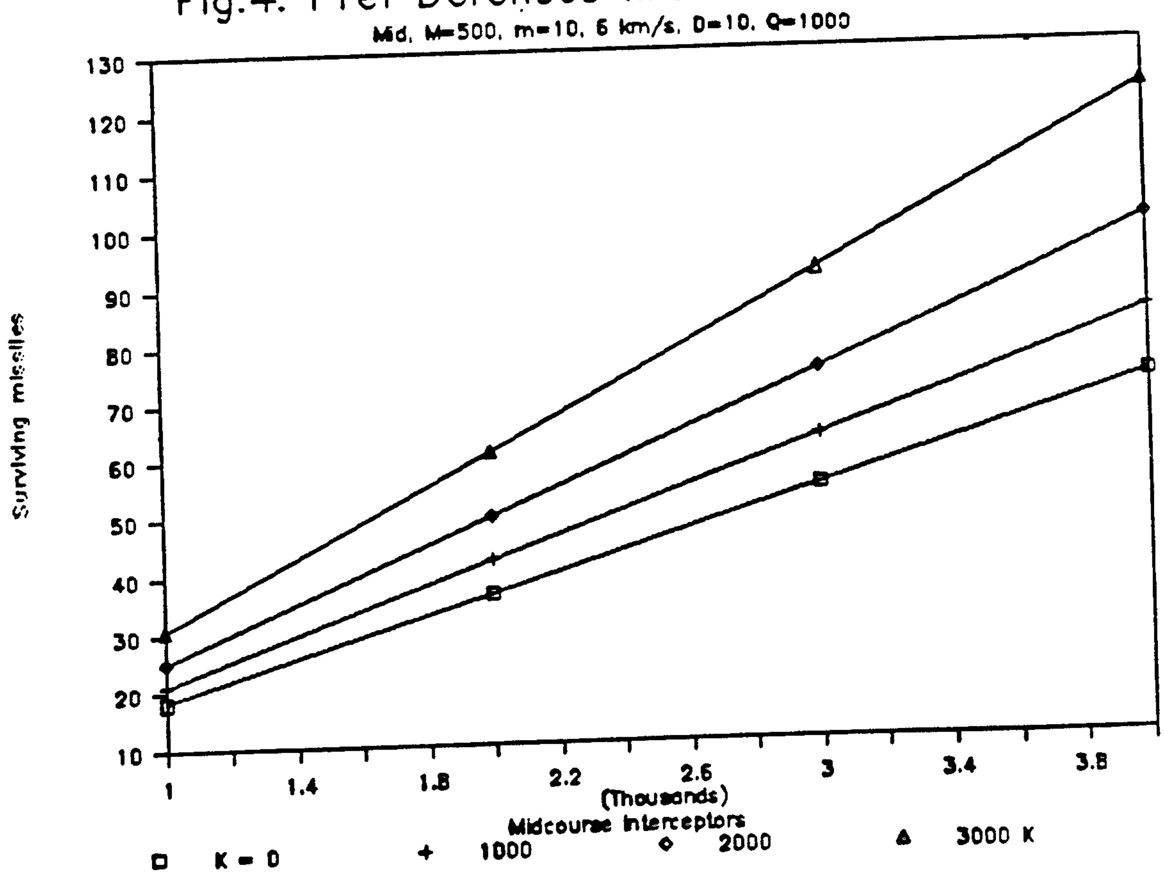

Fig.5. Pref. Defenses Midterm vs Decoys

Mid, M=500, m=10, 6km/s, Q=1000, I=1000

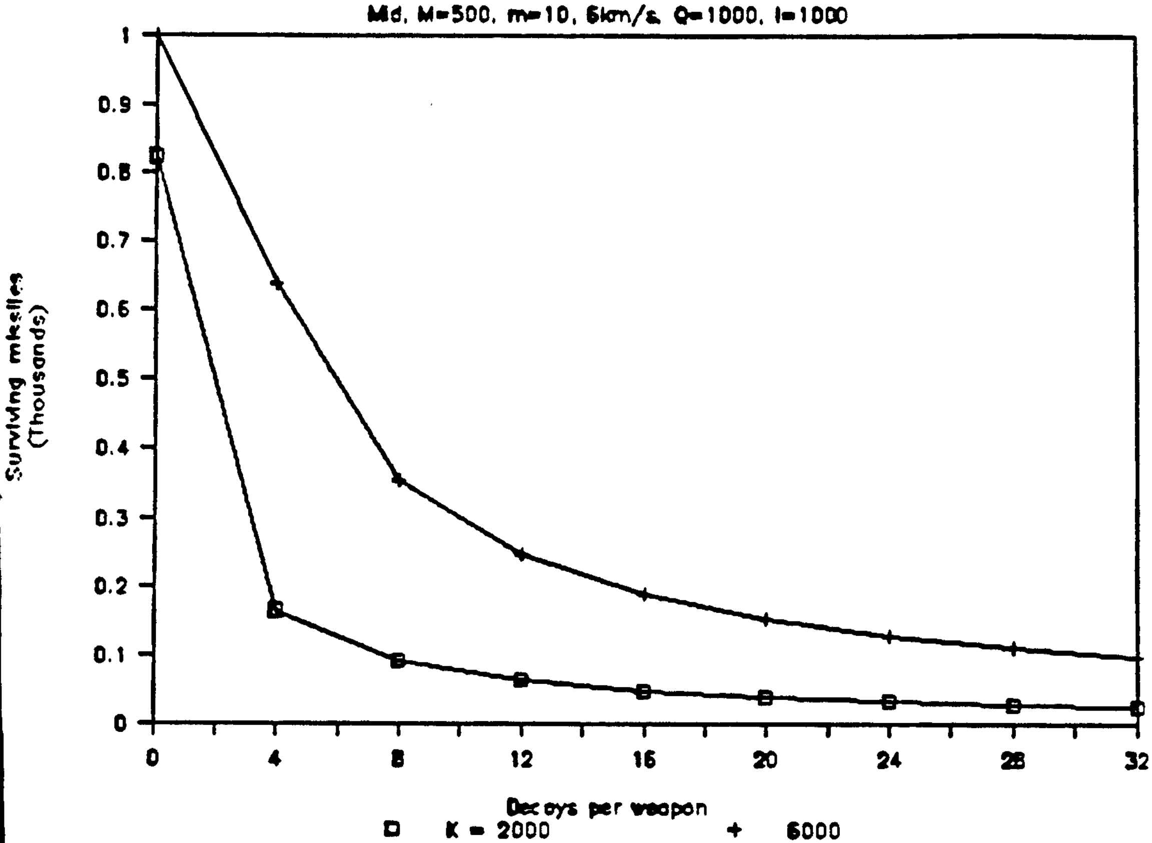

Fig.6. Pref. Defenses Near vs Boost

Mid, M=500, m=10, 6km/s, Q=1000, S=200